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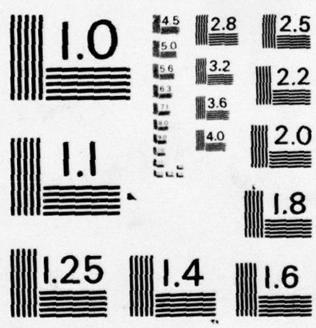

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THERMOMETRY AND TEMPERATURE SCALES: THE INSTITUTE OF PHYSICS LONDON MEETING IN JUNE, 1976

DR. T. A. KITCHENS, JR.

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- Noise Thermometry

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A review of a one-day (4 June 1976) meeting of the Low Temperature of the Institute of Physics in London on Thermometry. Discussions included mK adjustments in the near 4 K range, platenium resistance thermometry up to 273 K and fixed point superconducting thermometry.

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THERMOMETRY AND TEMPERATURE SCALES: THE INSTITUTE OF PHYSICS LONDON MEETING IN JUNE, 1976

On 4 June the Low Temperature Group of the Institute of Physics held a short one-day meeting in London on Thermometry. The timing of the meeting was excellent--one week before the Paris meeting of Working Group 4 of the Consultive Committee on Thermometry, CCT, the Group concerned with temperatures below 100 K. Consequently, two Americans interested in thermometry just happened to be passing through England, and the questions on the agenda of the Paris meeting could be discussed with a full knowledge of the results of the experiments initiated by the CCT. About 30 attended the meeting, a fifth of which were associated with the National Physical Laboratory (NPL) in Teddington, the British equivalent of the US National Bureau of Standards (NBS). I have noticed in North America that the number of people interested in precise and accurate thermometry is not large, but the lack of numbers is more than made-up by their intense interest in the subject. I now conclude that the European counterparts are from the same mold because the discussion was lively and detailed.

Professor C. A. Swenson [ISU (Iowa State University, Ames)] spoke on the thermodynamic temperature scale between 1-30 K. As most readers will remember there is a temperature scale, He^4(58), internationally recognized in 1958, which is a reconciliation of the He^4 vapor pressure (v.p.) scales used at the Kamerlingh Onnes Laboratory and the Naval Research Laboratory, both of which were established in 1955. Similarly, the hydrogen v.p. scale established in 1968 is designated as H_2(68). Swenson reviewed various recent absolute determinations of the boiling points of He^4 and H_2 to illustrate the difficulties with these v.p. scales. The table below resulted:

	He^4v.p.	H_2v.p.
Normal Boiling Point according to the respective accepted international v.p. scales, He^4(58) and H_2(68).	4.215 K	20.280 K
K. H. Berry, NPL Thermodynamic	4.2221 K	20.2714 K
R. A. Kamper, NBS-Boulder Noise Thermometry	4.222K	
N. Plumb, NBS-Wash. ["2-20" (1965)] (unpublished data)	4.222K	20.268 K
Acoustic Thermometry @ 1 MHz (corrected for new gas constant)	4.222K	20.275 K
A. R. Colclough, NPL Acoustic Thermometry @ 1 kHz	4.222 K	20.271 K
R. Sherman, Los Alamos Dielectric Constant	4.224 K	

These figures suggest that the He^4(58) scale is about 7 mK too low and that the H_2(68) scale is as much as 9 mK too high at the normal boiling point. In view of these difficulties, Working Group 4 is considering anew what type of thermometry is to be used as the primary standard and what scale is closest to the true thermodynamic temperature on that thermometer. Swenson presented a critique of magnetic, acoustic, resistance, and gas pressure thermometry.

Magnetic thermometry for temperatures above 4 K is being investigated at KOL (Kamerlingh Onnes Laboratory, Leiden), ISU, NBS, NPL, and at the National Measurements Laboratory (NML) in Sydney. These laboratories agree that the susceptibility χ of cerium magnesium nitrate, CMN, can be accurately described by $\chi = A+B/(T+\Delta)$ where $\Delta = 0.5 \pm 0.2$ mK below 3.2 K. Using this relation with $\Delta = 0.5$ mK to define a T_χ, T_χ is found to equal the thermodynamic temperature within a fraction of a millikelvin. χ deviates from this relation by about 3.5 K due to significant population of the I = 1/2 excited state at 35 K. Unfortunately, A and B are dependent on the fine details of the experimental geometry and must be determined by calibration at several fixed points or over a range of T. This lack of "transferability" and the difficult experimental problems, most of which are due to the sensitivity of χ to eddy currents and magnetic contamination such as a little condensed oxygen or magnetic impurities in or on the constructional materials, causes Swenson to feel that this type of thermometry is unsuitable as a primary standard

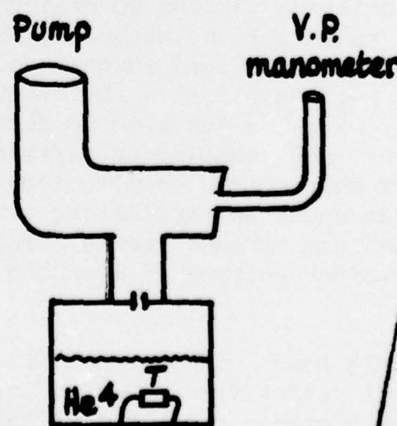
The researchers in these laboratories are also considering other magnetically dilute salts with larger χ for temperatures above 4 K. T. Cetas (NML) has used this technique up to 85 K. These salts are more complicated and require four or five free parameters to provide a T_χ with an accuracy of 0.1% over the temperature range. And the larger-χ salts do not avoid the fundamental difficulties listed above.

The NBS "2-20" scale was established by the work of N. Plumb in 1965 on the acoustic thermometer. It is designated as "2-20" because its useful range is over the otherwise difficult temperature range of 2 to 20 K. The acoustic thermometer is equivalent to the gas thermometer in that the velocity of sound is well approximated by the same simple kinematic theory as the idea gas law but it is dependent on an independent determination of the gas constant, R. Since 1965 a new value of R has been accepted, and the NBS "2-20" acoustic scale must be modified to account for the change. Plumb has always utilized 1 MHz and has just gathered new data which are smoother than those of 1965, yet the trend in these relative to the low-frequency acoustic data is somewhat disconcerting. A. R. Colclough (NPL) made low-f frequency (1 kHz) measurements which are quite smooth and more consistent with the NPL thermodynamic work, noise thermometry, and the older 1-MHz acoustic data. Swenson put more faith in the low-frequency data because of their consistency and the fact that the low-frequency electronics was better understood.

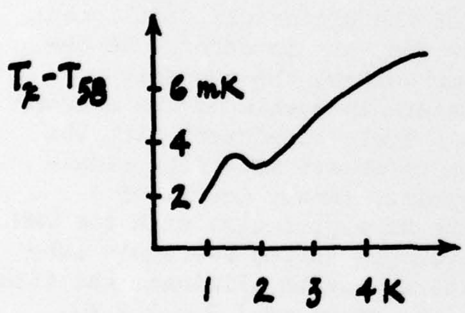
Resistance thermometry was briefly considered by Swenson. Certainly platinum resistance (PR) is not sensitive enough, and even a Rh-0.5%Fe resistor requires a very accurate bridge. Germanium resistance is much more sensitive, but we lack a fundamental understanding of its temperature dependence. It may prove to be a good transfer standard (see below).

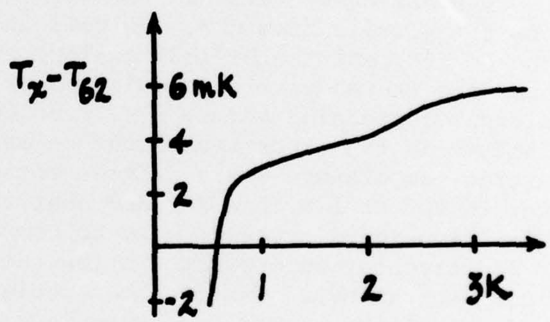
Swenson was in favor of retaining the gas thermometer because of its experimental ease--or at least because the experimental problems are well known--and because of the advent of the new digital pressure gauges working on the capacitance technique. The equation of state $PV = nRT\,[1+B(T)/V]$, where $B(T) = a + b/T$, is theoretically justifiable and, if used to define T_g, consistently provides a scale easily accurate to the thermodynamic temperature within a fraction of an mK. Still it is necessary to find a and b by calibration at, say, 4.222 K and 20.271 K, the normal boiling points of He^4 and H_2.

Dr. R. L. Rusby reviewed the work at NPL on the He^3 and He^4 v.p. scales and on the χ scale from CMN. He reminded us of the historical development of the $He^4(58)$ and the $He^3(62)$ scales, and how they are in error. He developed the thermodynamic calculation of T, emphasizing the necessity of consistent correction terms; i.e., the temperature integrals of the entropy and volume in the error terms must be made on a scale consistent with the resulting temperature scale. These correction terms are much more significant in He^3 at 1 K than for He^4 near the λ-point. Rusby described a carefully-designed cryostat used to compare the He v.p. scales with the CMN T_χ. The cryostat incorporates a few ideas developed during Swenson's sabbatical year at NPL. One of these design features was to eliminate the film-flow difficulties in He^4 v.p. measurements in the range of 1.3 - 2.2 K. The vapor pressure bulb and the refrigerating He^4 bath are arranged as illustrated below:



where the orifice above the bath is about 0.030", roughly one-tenth the diameter of the low-temperature pumping line. By supplying heat to the bath but maintaining the bath T constant, as seen by the resistance thermometer, by increasing the pump speed, they observed no change in the v.p. reading, indicating no pressure drop across the orifice in the usual operating conditions. This and other similar consistency checks have convinced them that this arrangement is sufficient for reliable v.p. measurements. The two CMN samples, one from NBS and the other from NPL, were composed of two hemispheres thermally linked with the bath with "coil-foil." The primary coil of the susceptibility meter utilized superconducting wire, and Rusby found it necessary to mount it on the 4.22 K shield before reliable measurements could be made. The two CMN samples were in good agreement except when compared with $He^3(62) = T_{62}$ near 1 K. Even there, the discrepancy was only twice the expected rms error. Rusby's results were roughly:





Dr. S. D. Ward (NPL) discussed the definition of the 1968 International Practical Temperature Scale (IPTS) based on PR over the range of 13.81 to 273.15 K. The scale utilizes various specified fixed points such as the normal boiling points and triple points of H_2, N_2, O_2 and H_2O within this range. The PR scale is then defined in terms of specified polynomial forms over four temperature regions, 13.81 - 20.28, 20.28 - 54.361, 54.361 - 90.188, and 90.188 - 273.15 K, with the function so described passing through the fixed end points and having a continuous first derivative everywhere from 13.81 to 273.15 K. If this sounds complicated--it is! A 1-mK error at one of the fixed points can cause an oscillating error in the IPTS which can be over 1.5 mK in magnitude at some remote point. And Ward is now wondering if a single fifth-order polynomial over the complete T-range wouldn't be better...

Ward is responsible for a six-year-old NPL project to intercompare platinum resistors and their scales from standard laboratories of all participating nations. Using a cryostat capable of handling the triple points as well as the boiling points, Ward has compared 18 resistors from eight countries plus 27 from NPL, or a total of 45 platinum resistors. The cryostat

allows 26 resistors, of which 16 are permanently part of the cryostat, to be intercompared simultaneously; and the resistance measurements are made at more than 40 specified temperatures over the complete range and with a specified Joule heating. The measurement is performed with a double Kelvin bridge, produced by Custers, which is precise to ±0.2 ppm.

Ward's report was fascinating--he could tell the source of the platinum used, whether it be Leeds and Northrup, Rosemont, or Tinsley. The intrinsic differences in the platinum caused discrepancies of not more than 4 mK. He was able to measure T with PR within 0.3 mK at 4.22 K with this apparatus. The maximum discrepancy between 45 resistors was 11 mK near 13 K, but most were within 4 mK everywhere. The maximum drift during the six years was 0.3 mK. It appears, in terms of the previous calibrations of these resistors, that the H_2 normal boiling point is within ±0.6 mK between the various national standards laboratories.

Dr. R. Hudson, standing in for Dr. R. Soulen, reviewed the NBS-Washington intercomparison of thermometers based on Johnson noise, nuclear magnetic resonance (NMR) and γ-ray anisotropy. The noise thermometry, developed by Soulen sometime ago, was incorporated into cryostats for the NMR and the γ-ray anisotropy thermometers for the intercomparison. The NBS noise thermometer uses a Superconducting Quantum Interference Device (SQUID) in a circuit such that the noise voltage across a resistor is converted into a noise frequency which modulates the "carrier" frequency of 24 MHz. It is this noise frequency that is observed to measure the temperature. The thermometer is currently useful below 4 K, and Soulen is planning to extend this work to higher T by using a higher-frequency SQUID.

The NMR thermometry involves the free induction decay of Cu^{63} and Cu^{65} nuclei. The beat phenomenon due to the differences in the resonant frequencies of these two species which occur in natural copper has been a problem, but in the 50 - 500 mK range the noise and NMR temperatures have agreed within 0.8 mK.

The γ-ray anisotropy work utilized the 1.17 MeV (4+ to 2+) and 1.33 MeV (2+ to 0) E2 transitions originating from Co^{60}. This technique is now well known, and the NBS-Washington program is coming to an end.

Hudson then reviewed the NBS-Washington project to provide not-too-expensive easy-to-use fixed-point references based on superconducting transitions. As most readers will know, the NBS SRM-767 consists of six superconductors, Pb, In, Sn, Al, An, and Cd, whose transitions may be detected by a simple $20 susceptibility circuit with a phase-sensitive detector. This covers the range from 0.515 K to 7.291 K with points accurate to ±1 mK. Currently NBS is considering a new single crystal Cd with a 10 μK-wide transition to replace the polycrystalline Cd, reference whose transition was nearly 2 mK wide. NBS is also considering extensions of the T range by Nb_3Sn (18.00 K), V_3Ga (14.30 K), Nb (9.299 K), $AuIn_2$ (0.203 K), $AuAl_2$ (0.150 K),

Ir (0.112 K), Be (0.024 K) and W (0.015 K). Hudson reviewed the metallurgical problems in obtaining reproducible and narrow transitions for these materials. He felt that they may have the Nb problem solved.

Hudson finished with a few remarks on interpolation thermometers. They should be easy-to-use and have digital output if possible. Some possibilities are a SQUID potentiometer circuit for Rh-0.5%Fe resistance or a gas thermometer incorporating a tunnel diode oscillator whose capacitor (or inductor) is controlled by a Bourdon tube.

P. Wolfendale (Automatic Systems Laboratories, Ltd., UK) spoke on the various double-bridge designs with resolution better than 0.01 ppm and other attributes appropriate for standards work. He then discussed the design that Automatic Systems hopes to introduce soon. I. Herbert (Oxford Instruments) spoke on the practical problems of thermometry seen by the producer of cryogenic equipment and the usual solutions. Oxford is building an interesting digital-readout resistance-thermometer circuit. It allows the user to specify ten linear regions for T versus resistance. This device should be especially useful for Rh-5%Fe resistance thermometry.

The next meeting of the Low Temperature Group will be at the University of Sussex in August, 1976. About every three years the Low Temperature Group awards The Simon Memorial Prize for distinguished work in experimental or theoretical low temperature physics. This year three Americans shared the prize for their discovery of the new superfluid phases of He^3 at Cornell in 1972, Professors D. M. Lee and R. C. Richardson and Dr. D. Oshenoff (who is now at Bell Laboratories, Murray Hill). The Sussex meeting will become a special Superfluid He^3 Symposium not unlike the Quantum Liquids Symposium held at Sussex some years ago. With leaders in this area of research expected to attend, it promises to be an interesting occasion.